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SPACECRAFT CHARGING AT GEOSYNCHRONOUS ORBIT - SOLUTION FOR ECLI--ETC(U)
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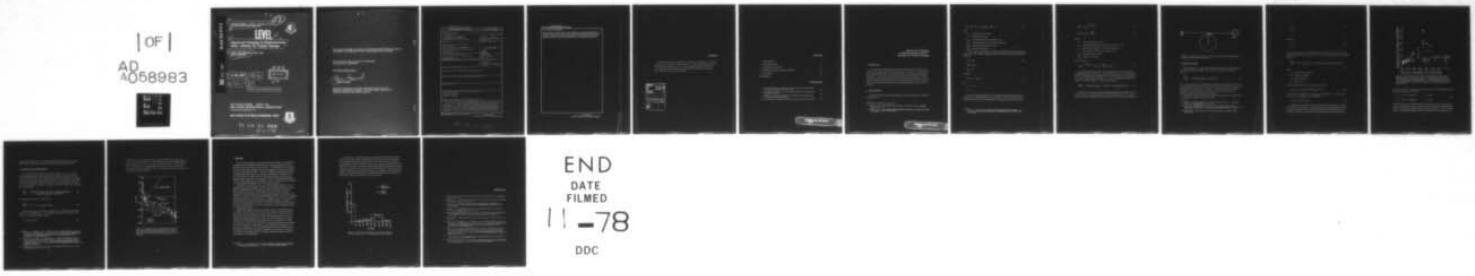

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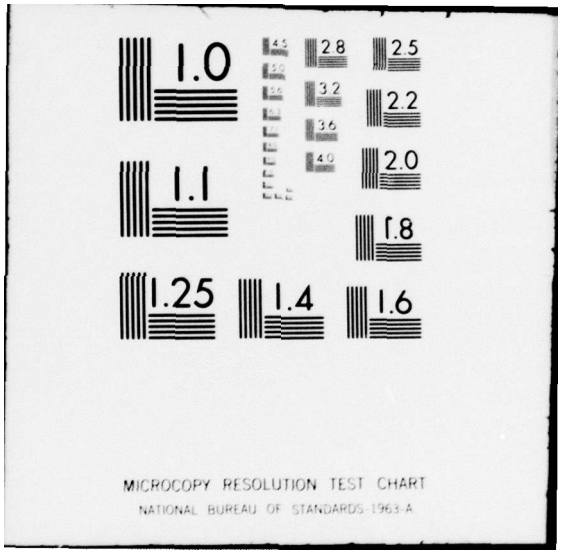
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LEVEL II

Spacecraft Charging at Geosynchronous Orbit—Solution for Eclipse Passage

HENRY BERRY GARRETT, CAPT, USAF
ALLEN G. RUBIN

Interim rept.

15 May 1978

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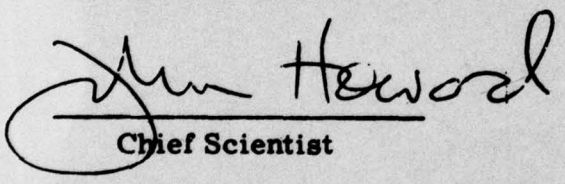

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Rapid variations in spacecraft potential are observed on entry and exit from the earth's shadow. Generalized equations, based on elementary plasma probe theory, are developed which make quantitative estimates of these potentials as a function of satellite position in the earth's penumbra, and are compared with data from the ATS-5 and ATS-6 geosynchronous satellites. The agreement between the observations and the predictions results from the approximate constancy of the ratio of the ambient ion to electron current

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20. Abstract (Continued)

during injection events. Due to the significant size and shape differences of the ATS-5 and ATS-6 satellites, the results are applicable in many space physics situations such as estimating the effects of electron beams on satellite potential and of spacecraft charging on very large space structures.

Preface

The authors would like to thank Drs. W. Burke, E.C. Whipple, A.J. Dessler, W. Olson, and D. Hardy for their comments. C. Pike provided the impetus and encouragement for the study. Ms. J. Fink prepared the data for analysis. Dr. S.E. DeForest provided the ATS-5 and ATS-6 data and spent many invaluable hours explaining its use and interpretation.

Contents

Illustrations

Spacecraft Charging at Geosynchronous Orbit— Solution for Eclipse Passage

1. INTRODUCTION

The interactions between spacecraft and the ambient space environment have become an increasing problem to the space physics community. The best known of these environmental interactions is that resulting from spacecraft charge buildup (DeForest[1]). In this report, simple plasma probe theory will be used to develop equations which allow estimations of the potential that exists between a spacecraft and the ambient medium in the presence of a varying photoelectron flux. The variations are compared with observations from the geosynchronous satellites ATS-5 and ATS-6.

2. BASIC EQUATIONS

The basic equation describing the spacecraft charging phenomenon is (Whipple,[2] and DeForest[1]):

(Received for publication 11 May 1978)

1. DeForest, S. E. (1972) Spacecraft charging at synchronous orbit, J. Geophys. Res. 77:651-659.

2. Whipple, E. C. (1965) The Equilibrium Electric Potential of a Body in the Upper Atmosphere, NASA X-615-65-296.

$$J_E - (J_I + J_{SE} + J_{SI} + J_{BSE} + J_{PH}) = 0 \quad (1)$$

where

J_E = Incident electron current

J_I = Incident ion current

J_{SI} = Secondary electron current due to ions

J_{SE} = Secondary electron current due to electrons

J_{BSE} = Back-scattered electron current

J_{PH} = Photoelectron current.

To first order, for the range of currents and potentials observed at geosynchronous orbit, the secondary and backscattered currents are approximated by linear relations:

$$J_{SE} \approx a\, J_E \quad (2)$$

$$J_{BSE} \approx b\, J_E$$

$$J_{SI} \approx c\, J_I$$

such that:

$$x\, J_E - y\, J_I - J_{PH} = 0 \quad (3)$$

for:

$$x = 1 - a - b$$

$$y = 1 + c \quad .$$

From probe theory (Chen[3]) for a thick sheath around a spherical probe or in the absence of a sheath (DeForest[1]), the current to a probe as a function of the ambient current and spacecraft potential for a negatively charged spacecraft is:

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3. Chen, F. F. (1965) Electric Probes, Plasma Diagnostic Techniques, R. H. Huddlestone and S. L. Leonard (Ed.), Academic Press, Inc., New York, pp 113-200.

$$J_E(V) = J_{EO}\, e^{-|qV|/T_E} \tag{4}$$

$$J_I(V) = J_{IO}\left(1 + \frac{|qV|}{T_I}\right) \tag{5}$$

where

V = Spacecraft potential in volts

T_E = Maxwellian temperature of electrons in electron volts

T_I = Maxwellian temperature of ions in electron volts

q = Unit charge such that qV is in electron volts

J_{EO} = Ambient electron current

J_{IO} = Ambient ion current.

Eq. (3) becomes:

$$x\, J_{EO}\, e^{-|qV|/T_E} - y\, J_{IO}\left(1 + \frac{|qV|}{T_I}\right) - J_{PH} = 0 \tag{6}$$

J_{PH}, the photoelectron current, can be expressed as a function of the pre-eclipse photoelectron current, J_{PO}, and an attenuation function f representing the fraction of sunlight falling on the spacecraft. It is convenient to express this fraction in terms of the minimum altitude, X_m, for the ray between the satellite and the center of the sun (Figure 1). Thus Eq. (6) becomes:

$$\frac{|qV|}{T_I} = -\,\mathrm{Ln}\left[(y/x)(J_{IO}/J_{EO})(1 + |qV|/T_I) + (1/x)(J_{PO}/J_{EO})\, f(X_m)\right] \quad . \tag{7}$$

Equation (7) is the basic spacecraft charging equation in the presence of photoelectron emission. Assumptions will be made that reduce Eq. (7) to an analytic expression giving the spacecraft potential as a function of the electron temperature.

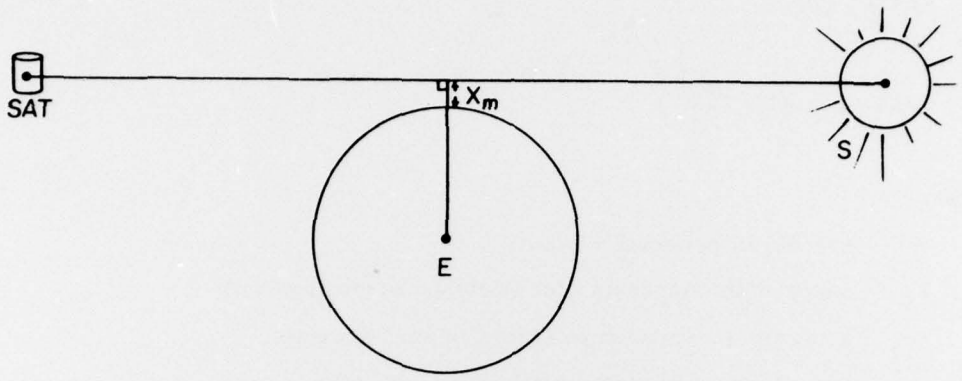

Figure 1. The Altitude X_m Above the Earth of the Minimum Ray Path Between the Satellite and the Center of the Sun

3. POTENTIAL IN ECLIPSE

When a spacecraft is in the earth's shadow, the photoelectron flux approaches zero (scattered light, moonlight, etc., may still be present) so that Eq. (7) becomes:

$$\frac{|qV_o|}{T_E} = - \text{Ln}\left[(y/x)(J_{IO}/J_{EO})(1 + |qV_o|/T_I)\right] \quad . \tag{8}$$

T_E, T_I, J_{IO}, and J_{EO} were calculated for 21 electron and ion spectra from ATS-5 and for four spectra from ATS-6 for intervals immediately preceding eclipse entry and immediately following exit from eclipse. These spectra cover the energy ranges 50 eV to 50 keV and 1 eV to 80 keV respectively (see DeForest and McIlwain,[4] and Mauk and McIlwain[5] for details).

Parameters x and y for the range of observed parameters are estimated from formulas given in Whipple[2] and Garrett[6] to be:

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4. DeForest, S. E., and McIlwain, C. E. (1971) Plasma clouds in the magnetosphere, J. Geophys. Res. 76:3587-3611.

5. Mauk, B. H., and McIlwain, C. E. (1975) ATS-6 UCSD auroral particles experiment, IEEE Trans. Aerospace and Electronic Systems, AES-11(No. 6): 1125-1130.

6. Garrett, H. B. (1978) Spacecraft Potential Calculations – A Model, AFGL-TR-78-0116.

$$a \approx 0.4 \tag{9}$$

$$b \approx 0.2$$

$$c \approx 3$$

Therefore:

$$x \approx 0.4 \tag{10}$$

$$y \approx 4 \quad .$$

For the eclipse potentials corresponding to the 25 intervals, the ratio $|qV_o|/T_I$ is in general less than 1. Therefore, $\mathrm{Ln}(1 + |qV_o|/T_I)$ is approximately 0. Equation 8 reduces to:

$$\frac{|qV_o|}{T_E} = \mathrm{Ln}\left[(1/10)(J_{EO}/J_{IO})\right] = \mathrm{Ln}\left[(1/10)(n_E/n_I)(T_E/T_I)^{1/2}(m_I/m_E)^{1/2}\right] \tag{11}$$

where

n_E = Ambient electron density

n_I = Ambient ion density

m_E = Mass of electron

m_I = Mass of ion .

For the data studied, $T_I \approx 2.5\ T_E$ and $n_E \approx n_I$ so that:

$$J_{EO}/J_{IO} = (n_E/n_I)(T_E/T_I)^{1/2}(m_I/m_E)^{1/2} \approx 25 \quad . \tag{12}$$

For the 25 events studied, the ratio J_{EO}/J_{IO} is actually 24 ± 7. As the current ratio enters as a logarithm, Eq. (11) becomes:

$$|qV_o| \approx T_E\ \mathrm{Ln}(2.5) \approx T_E \quad . \tag{13}$$

In Figure 2, the electron temperature (assumed to be Maxwellian) is plotted versus the observed potential. An expression linear in the ambient temperature was fit to the data by the least squares method (the two marked points were not included as the plasma is believed to have changed between the measurement of

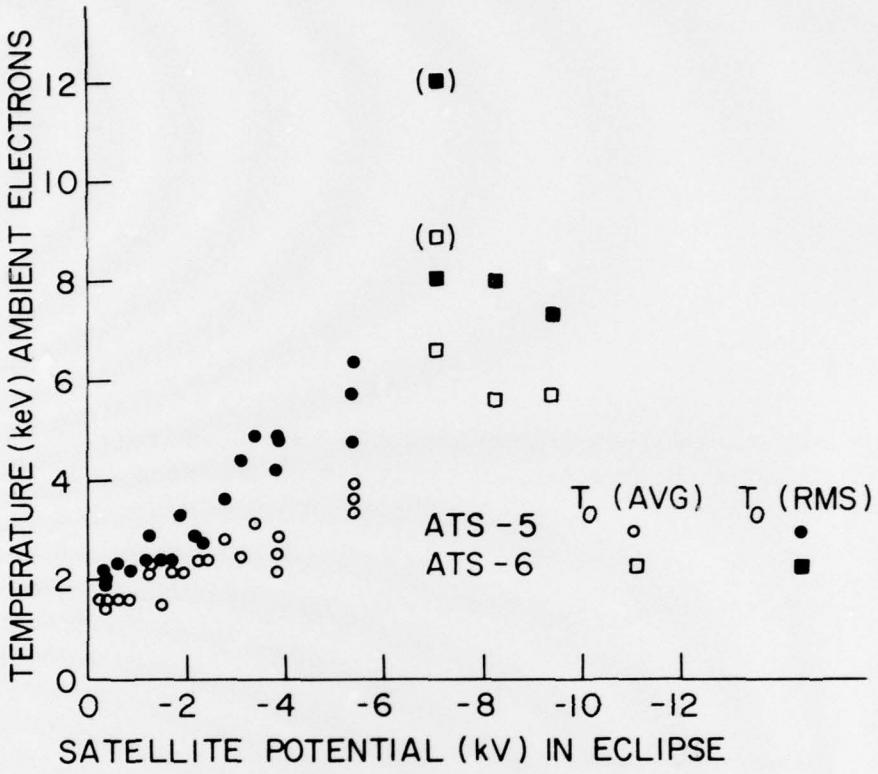

Figure 2. The Observed Temperature of the Ambient Electrons vs the Satellite Potential in Eclipse. T_o(AVG) is given by 2/3's of the ratio of the energy density to the number density. T_o(RMS) is given by 1/2 of the ratio of the energy flux to the number flux. The difference between these two temperatures is a measure of the adequacy of a Maxwellian approxi-approximation

T_E and the potential). Depending on which definition of the temperature is used the fits and correlation coefficients are:

$$V_o^* = 1391 - 1.63\ T_E(\text{AVG}) \qquad (r = 0.86)$$

$$V_o^* = 1828 - 1.29\ T_E(\text{RMS}) \qquad (r = 0.92) \qquad (14)$$

These relationships not only demonstrate the validity of Eq. (13), but imply the existence of a threshold electron temperature above which the satellite potential is linear. Such behavior, though not explicit in our simple theory, is due to the fact that at an intermediate energy (usually a few hundred eV), the secondary yield is

greater than 1 (Rubin et al[7]). The electron temperature must be several times greater than this threshold energy before significant charge buildup occurs.

4. POTENTIAL DURING ECLIPSE PASSAGE

As a spacecraft enters and exits the earth's penumbra, it sees a varying illumination generating a varying photoelectron current as the sun's disc is obscured by the limb of the earth. The percentage of solar illumination as a function of X_m seen by a satellite at geosynchronous orbit is plotted in Figure 3 (the attenuation function is based on the work of Garrett[9] and, as the details are not of concern to this generalized treatment, the reader is referred to that paper). Dividing Eq. (7) by Eq. (8):

$$\frac{V(X_m)}{V_o} \approx \frac{\mathrm{Ln}[(y/x)(J_{IO}/J_{EO})(1 + |qV|/T_I) + 1/x(J_{PO}/J_{EO})\, f(X_m)]}{\mathrm{Ln}[(y/x)(J_{IO}/J_{EO})(1 + |qV_o|/T_I)]} \tag{15}$$

Estimating as before and, as $|qV| \lesssim |qV_o|$:

$$\frac{V(X_m)}{V_o} \approx -\,\mathrm{Ln}[.4 + 2.5\,(J_{PO}/J_{EO})\, f(X_m)] \tag{16}$$

The ratio J_{PO}/J_{EO} is not known accurately as it is a function of the material and structure of the spacecraft. From Whipple,[2] Grard et al,[8] DeForest,[1] and Garrett,[9] a reasonable range of values is:

$$1.6 \lesssim J_{PO}/J_{EO} \lesssim 16 \tag{17}$$

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7. Rubin, A.G., Rothwell, P.L., and Yates, G.K. (1978) Reduction of spacecraft charging using highly emissive surface materials, Proc. 1978 Symposium on the Effect of the Ionosphere on Space and Terrestrial Systems, Naval Research Lab., Washington D.C.

8. Grard, R.J.L., Knott, K., and Pedersen, A. (1973) The influence of photoelectron and secondary electron emission on electric field measurements in the magnetosphere and solar wind, Photon and Particle Interactions with Surfaces in Space, R.J.C. Grard (Ed.), D. Reidel Publishing Co., Dordrecht, Holland, pp. 163-189.

9. Garrett, H.B. (1978) Effects of a Time-Varying Photoelectron Flux on Spacecraft Potential, AFGL-TR-78-0119.

In Figure 3, Eq. (16) is plotted for $f(X_m)$ given by Garrett[9] and for $J_{PO}/J_{EO} = 1.6$ and 16. Also shown are data from ATS-5 and ATS-6 for the 25 eclipse passages. The observations are subject to a large (~25 km) error in X_m, as the orbits of ATS-5 and ATS-6 were not updated sufficiently often to allow a more accurate position determination (Garrett[9]). Even so, the predicted variation in parameters brackets the actual observations.

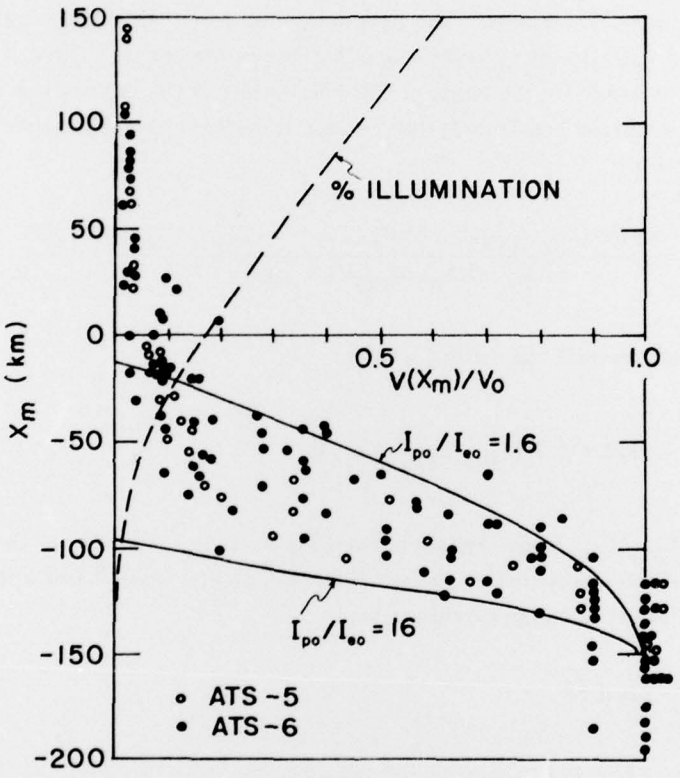

Figure 3. The Ratio of the Varying Potential to the Maximum Potential When the Spacecraft Were in Eclipse. Also shown are the percent illumination (same scale as $V(X_m)/V_o$) and the predicted curves for I_{po}/I_{eo} values of 1.6 and 16

5. DISCUSSION

In the previous sections, we have presented equations (Eq. (13) and (16)) that approximate ATS-5 and ATS-6 observations of the varying potential that exists between the spacecraft and the ambient plasma. We believe that this is primarily the result of the rough constancy of the ratio J_{IO}/J_{EO} and the fact that variations in this ratio enter as a logarithm. Further, it is tacitly assumed that T_I and T_E, the Maxwellian temperatures, have meaning. Although these assumptions are not valid at all times at geosynchronous orbit (particularly at quiet times when non-Maxwellian ring currents are observed), they are adequate following plasma injections when a satellite is near midnight. As this is a prerequisite for charging to occur during eclipse passage, Eqs. (13) and (16) are valid.

Equations (13) and (16) are of use in many space physics problems. As an example, given T_E, the potential in eclipse can be estimated by Eq. (13). Equivalently we have plotted the frequency of occurrence of potentials in eclipse for ATS-5 and ATS-6 for 4 years. With Figure 4 and Eq. (16), the occurrence frequency of various potential levels as the spacecraft entered into eclipse can be estimated for the same 4 year period (Rubin and Garrett[10]). As ATS-5 is a spinning cylindrical shape (1.3 m in diameter by 2 m in length) and ATS-6 is a large (10 m) spin-stabilized dish antenna, the equations are also applicable to a variety of problems and simple space structures. For instance, by equating the photoelectron current to an electron beam, Eq. (13) and (16) can be used to simulate the effects of a varying electron beam.

Although the scaling to large space structures may not be completely valid, the results of Eq. (13) and (16) may be used in principle to estimate the potential that would exist between the ends of a large space structure. This can be most readily visualized by assuming the structure to be approximated by two spheres separated by a distance equal to that of the structure, and connected by a long cable having the electrical loading characteristics of the structure. For infinite resistance, Eqs. (13) and (16) can be used to estimate the potential on each sphere as it passes into eclipse. Assuming the distance between the two spheres to be equal to their difference in X_m, the potential difference between the two ends can be estimated as they pass into eclipse. Depending on the exact nature and size of the structure, this simple analogy would predict potentials as high as -20,000 V, a clear hazard to the spacecraft.

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10. Rubin, A.G., and Garrett, H.B. (1978) A Statistical Study of Eclipse Potentials for ATS-5 and ATS-6, to appear as AFGL In-House Report.

In conclusion, elementary probe theory suggests basic relations between the electron temperature (assumed Maxwellian) and the spacecraft potential relative to the ambient plasma when the spacecraft is in the earth's shadow. Relations describing the potential variations as the spacecraft passes into eclipse are derived Observations from ATS-5 and ATS-6 support these derivations and indicate that the reason for agreement, is because the ratio of the ambient ion to electron current is roughly constant for injection events and enters as a logarithm. Provided that the results are of general applicability, they can be used to estimate the potentials on large space structures and the effects of electron beams.

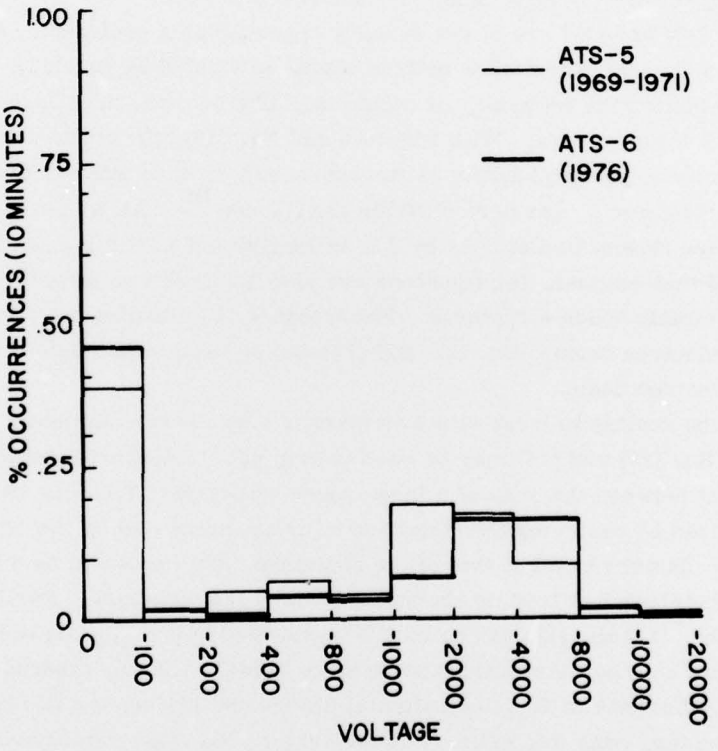

Figure 4. The Occurrence Frequency of Eclipse Potentials for ATS-5 and ATS-6. 10 minute averages were employed

References

1. DeForest, S. E. (1972) Spacecraft charging at synchronous orbit, J. Geophys. Res. 77:651-659.

2. Whipple, E. C. (1965) The Equilibrium Electric Potential of a Body in the Upper Atmosphere, NASA X-615-65-296.

3. Chen, F. F. (1965) Electric Probes, Plasma Diagnostic Techniques, R. H. Huddlestone and S. L. Leonard (Ed.), Academic Press, Inc., New York, pp. 113-200.

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